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A Machining Process Planning Activity Model for Systems Integration

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Abstract

A key issue of integrating process planning systems with design systems and production planning systems is how to overcome barriers in data exchange and sharing amongst software systems. A machining process planning activity model was developed at the National Institute of Standard and Technology to address some of the barriers. This model represents functional components and data requirements in process planning systems. The purpose of the model is to create the context in which data requirements and data flow for NC machining process planning are defined. The model was developed as a unification of many previously developed process planning activity models.

Key Words: activity modeling, machining process, NC, process planning, system characterization, system integration

1 Introduction

Data incompatibility between currently available manufacturing software systems is a major barrier in systems integration. Data exchange between any two systems cannot always be efficiently done. Each manufacturing software system has its own proprietary data format, which is often not available to users. Even in systems which make their data formats available to users, data definitions provided by one system might be only suitable to that particular system and incompatible with others. In such a situation of data incompatibility, a smooth work flow from computer-aided design to computer-aided process planning to computer-aided production planning is not possible. Developing an integration mechanism is important to achieving design, process planning, and production planning systems integration.

An open, neutral, and extensible data model is an effective mechanism to resolve a data incompatibility problem. A data model is a data representation specification that captures the form, function, and definition of all the pieces of information. The data model also captures the relationships between pieces of information. In order to provide sharable data among commercial systems, the data should be available to all vendors in a neutral format that does not bias any particular product. In addition to the openness and neutrality, the extensibility of the data model is also a requirement. An extensible data model can incorporate new data that meet future data needs. With an open, neutral, and extensible data model, data sharing and smooth data exchange among software systems are possible.

Developing an activity model is the first step to developing a neutral data model. An activity model is a representation of the functions and data interface requirements for an engineering (or business) process. The activity model sets the context in which some data are exchanged between functions and other data, as resources, are shared by functions. Activity modeling allows data modelers to capture prerequisite information for developing data models.

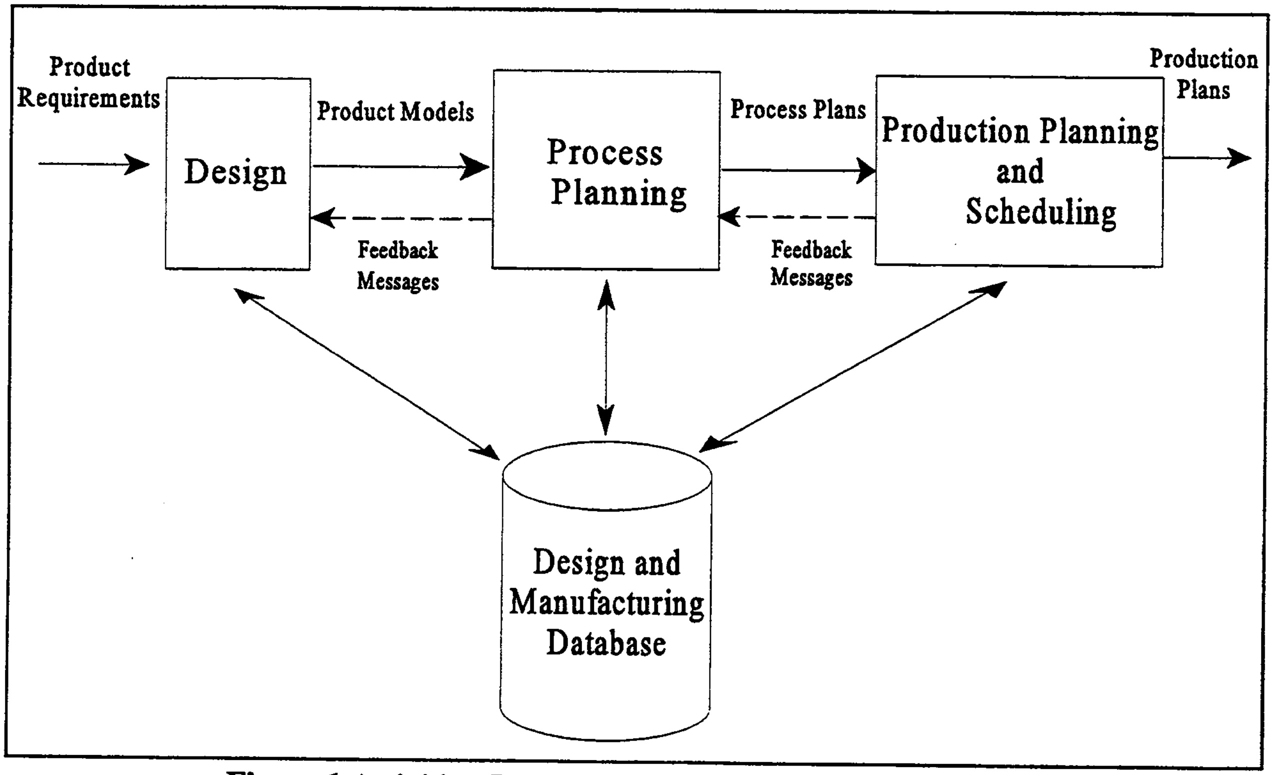

Figure 1 Activities, Data, and Message Flow in Manufacturing

Process planning is an essential link between design and production planning in the product development process. The high-level relationships between design, process planning, and production planning activities are shown in Figure 1, which represents a computer-integrated manufacturing system. In this system, design is an activity to generate the product model of a product based on the product's functional requirements. Process planning is an activity to generate process plans which is the detailed specification for the manufacture of a part meeting the design specifications. Production planning is an activity that generates schedules for specific production facilities and resources to perform the process plan specifications. If there are manufacturability problems with the design, messages will be sent to the designer as feedback from process planning. If production plans and schedules cannot be created, messages will be sent to the process planner as feedback from production planning. As shown in the figure, the crucial transition from engineering design to shop-floor production is process planning, which converts the product design into a manufacturing action plan.

This paper presents an activity model of a machining planning process. The model represents the machining planning subactivity in the context of an embarked effort at NIST for integration of manufacturing software systems [1]. Within this NIST effort, an overall activity model was developed to describe engineering design, manufacturing engineering, and production engineering activities [2]. The activity model presented in this paper contains more detailed process planning information with more levels of decomposition and is an extension of the manufacturing engineering portion of the overall activity model. In addition to its extending the overall model, the model was also created as a unified model with some functions that are missing from previously published process planning-related models. The activity is documented in the form of IDEF0, which is a functional modeling methodology [3]. In this model, the process planning activity is specifically designed for machining using numerically controlled machining centers, which are commonly used in automated production systems.

This report has four sections, including this introduction. Section 2 is a review of available machining process planning activity models. Section 3 describes the process planning activity model shown in IDEF0 diagrams. Section 4 summarizes the work and describes future activities.

2 A Review of Process Planning Activity Models

This section reviews available activity models developed for specifying process planning activities. These models were developed in industry, academia, and standards committees, in the machining, sheet metal working, and assembly application areas. The need for consolidating these models and adding new functions is also addressed at the end of the section.

2.1 CAM-I Activity Model

The CAM-I model [4] is an IDEF0 model which describes the process planning activity for mechanical part manufacturing. It describes the following functions: extracting information in product model data for manufacturing, selecting processes and sequencing the processes, selecting machines and tools, specifying workpiece setups, developing a list of operations, and evaluating the generated process plans. In extracting product model data, the subactivities are extracting geometric information, surface information, material information, and tolerance information. In selecting and sequencing processes, the subactivities are process selection and ordering. For process planning needs, input data are grouped into product model data (including geometry, material, tolerance, and surface property) and process-related data (including manufacturing resource availability and process capability specification). The output of the described process planning activity model includes process plans and production scheduling plans. Tolerancing standards and manufacturing analysis rules are indicated as controls, and part analysis programs and process planning procedures are shown as mechanisms.

The following functions are not addressed: intermediate feature and tolerance specification, shop-floor routing planning, design change recommendation, and tooling.

2.2 IMPPACT Activity Model

A model defining an activity model and a data model was developed by the IMPPACT project [5]. The application area is in the manufacturing of discrete parts, such as machined, sheet metal, and cast parts. The model describes manufacturing process planning, fixture planning, and operation planning, including functions such as product model recognition, specific manufacturing process selection, material stock selection, operation and fixture definition, NC code generation, and manufacturing time estimation. This model identifies the types of data necessary, such as material, tooling, machine, and fixture, for process planning within the IMPPACT architecture which defines an integrated design and manufacturing environment.

Only high level functions of the activity model are shown in the referenced IMPPACT document. Based on the available information in the document, many detailed functions need to be decomposed from the high level activity model to become useful to others. All the functions that are not addressed in the CAM-I model are also not addressed in this model.

2.3 Airframe Manufacturing Process Activity Model

The Automated Airframe Assembly Program (AAAP) [6, 7] developed an activity model to describe functions in airplane frame design, manufacturing planning, assembly planning, and inspection planning. This model includes manufacturing process planning subactivities, such as the selection of machines, tools, and fixtures, the determination of operation sequences, tooling design, and the generation of machine tool control programs. Input data include a product model, manufacturing capability, existing process plans, standards, and procedural guidelines. Output data are NC programs, manufacturing plans, and a report of potential problems. The model is captured in IDEF0 diagrams.

The process planning portion of the AAAP activity model was not specifically created for machining. Thus, some essential functions are not included in the model, such as material stock selection, machining feature derivation, setup determination, tolerance analysis, and cost estimation.

2.4 STEP AP 213 Activity Model

STEP AP 213 [8] has an activity model for NC machining process planning. The model describes machining resource selection, machining operation plan development, process plan validation and approval. The purpose of the model is to develop information packages, such as tooling data packages, machining data packages, and inspection data packages. The input data to this model include product definition data, orders, existing process plans, standard tooling and cost estimation model, and process capability data. The output data include process plans and manufacturing resource requirement data packages as aforementioned. The activity model describes the context under which a standard data model is defined for the exchange of NC machining process plans among heterogeneous systems. The model is also captured in IDEF0 diagrams.

The activity model in this STEP AP is focused on the representation of administrative data. Machining feature derivation from the design specification, cost estimation, shop-floor routing, and design change recommendations are not addressed.

2.5 STEP AP 224 Activity Model

STEP AP 224 [9] includes an activity model for manufacturing mechanical parts. This model was developed for defining the context under which the data are transferred from computer aided design systems to computer aided process planning systems. The model includes the following major subactivities: managing the administrative data, packaging product definition data for process planning, generating manufacturing data, and creating shop floor operations. Only the subactivity of packaging product definition data is within the scope of the AP. It includes capturing special notes, extracting manufacturing features from part shape, defining surface finish and hardness, and extracting tolerances. Although the process planning subactivities are out of scope, the model mentions the following activities: selecting manufacturing resources, defining routing, creating a manufacturing bill of materials, and defining detailed manufacturing operations. Similar to the STEP AP 213 model, the model is captured in IDEF0 diagrams.

The following activities are not addressed in the activity model: cost estimation, shop-floor routing, and design change recommendations. Overall the activity model is fairly complete.

In summary, all the above mentioned models capture basic functions in process planning. However, they do not address some present industrial needs. An enhanced machining process planning model is needed to address what the models do not include, namely, machining feature derivation, intermediate machining feature generation, tolerance specification for intermediate features, shop-floor routing planning, material stock selection, setup determination, cost estimation, shop-floor routing, and design change recommendations.

3 Machining Process Planning Activity Model

This section describes a machining process planning activity model that consolidates all the activity models reviewed in the previous section and includes additional features that are needed to address current CAPP system and integration needs. The inspection activity is not addressed in this model, and an inspection activity model can be found in another report [10]. This model, developed using IDEF0, specifies functions and data requirements for machining process planning. A glossary for the model has also been developed. This activity model is defined for machining a single part in a factory. The model addresses the development of process sequences, machining operations, shop floor routings, numerically controlled machine tool program generation, and plan/program validation. It also includes cost/time estimation and material requirements.

3.1 Machining Process Planning Activity Model

This section presents a model of machining process planning activities, captured in IDEF0 diagrams. The model defines the scope, functional components, and data requirements for developing machining process planning systems. The IDEF0 model is represented by eight diagrams showing activities at different levels of abstraction. The diagrams shown on the next eight pages are named A-0, A0, A1, A2, A22, A3, A4, and A5 (Figures 2 - 9).

It is important to note that IDEF0 diagrams are often interpreted to imply a strict sequence of activities. That is not the intention in this case. Rather, the numerous data flows representing feedback from one activity to another are expressly omitted to avoid cluttering the diagrams. Thus, for example, in Figure 3, each of the activities A1-A5 should be considered to be providing data to each of the other activities in the figure.

Diagram A-0 models the context in which the machining process planning activity takes place. Activity A0 performs machining process planning. The activity is to create process plans for part machining based on a part design. The activity has input data from a product model (e.g., in engineering drawing or CAD models), tooling and material inventory data, and process change requests. The activity also requires controls of cost constraints set by company or product planners. Mechanisms of the activity are machining resource descriptions, standard cost references, standard process models, machinability data, and material stock descriptions. The outputs of the machining process planning activity are cost estimation, validation run requirements, stock material specification, resource requirements, routing plans, process plans, machine control programs, and design change requests.

The overall activity on level A-0 is decomposed into five activities (A1 — A5) in Figure 3, Diagram A0. This diagram shows the relationships among the activities and the data inherited from the upper level (A-0).

Activity A1, shown on diagram A0 and expanded in diagram A1, generates process sequences. The activity is to select and sequence a set of processes to transform material stocks to finished parts. Alternative sets of sequenced processes may be produced.

Activity A2 generates operations. The activity is to develop detailed machining instructions for each operation in the process routing. The information used in an operation includes machining surfaces/features, workpiece setups, machines, tools and fixtures selected, machining dimensions and tolerances, etc.

Activity A3 generates shop floor routings. The activity is to determine the shop floor configuration and means of workpiece transportation. Shop floor specifications include work centers in which workpieces are machined and corresponding workpiece travel itineraries.

Activity A4 generates control programs. The activity is to create computer programs that control machine tools and workpiece handling and transportation machines on the shop floor. The computer code includes the numerical control (NC) programs for the machining centers, robot programs, automatic guided vehicles (AGV) programs, etc.

Activity A5 validates plans and programs. The activity is to verify, recommend changes to, approve or disapprove the generated process plans, routing plans, NC programs, robot programs, and AGV programs to ensure the correctness of these plans and programs for part production.

Figure 4 shows the decomposition of activity A1 into four activities (A11 — A14). Activity A11 specifies material stock. The activity is to select the type of stock material and define the geometry of the stock. The material stock specification, the output data, is used in the next activity.

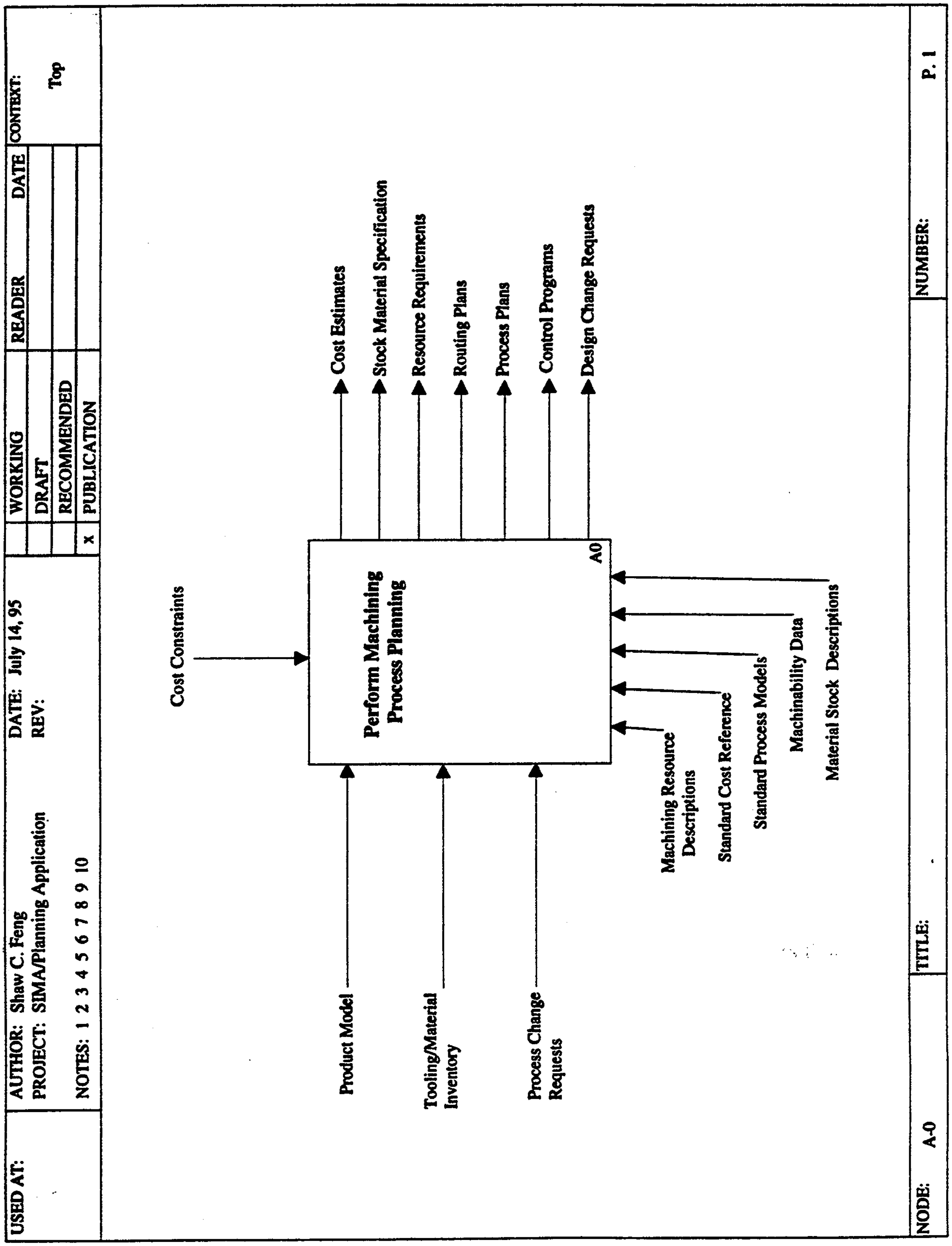

Figure 2 Diagram A-0

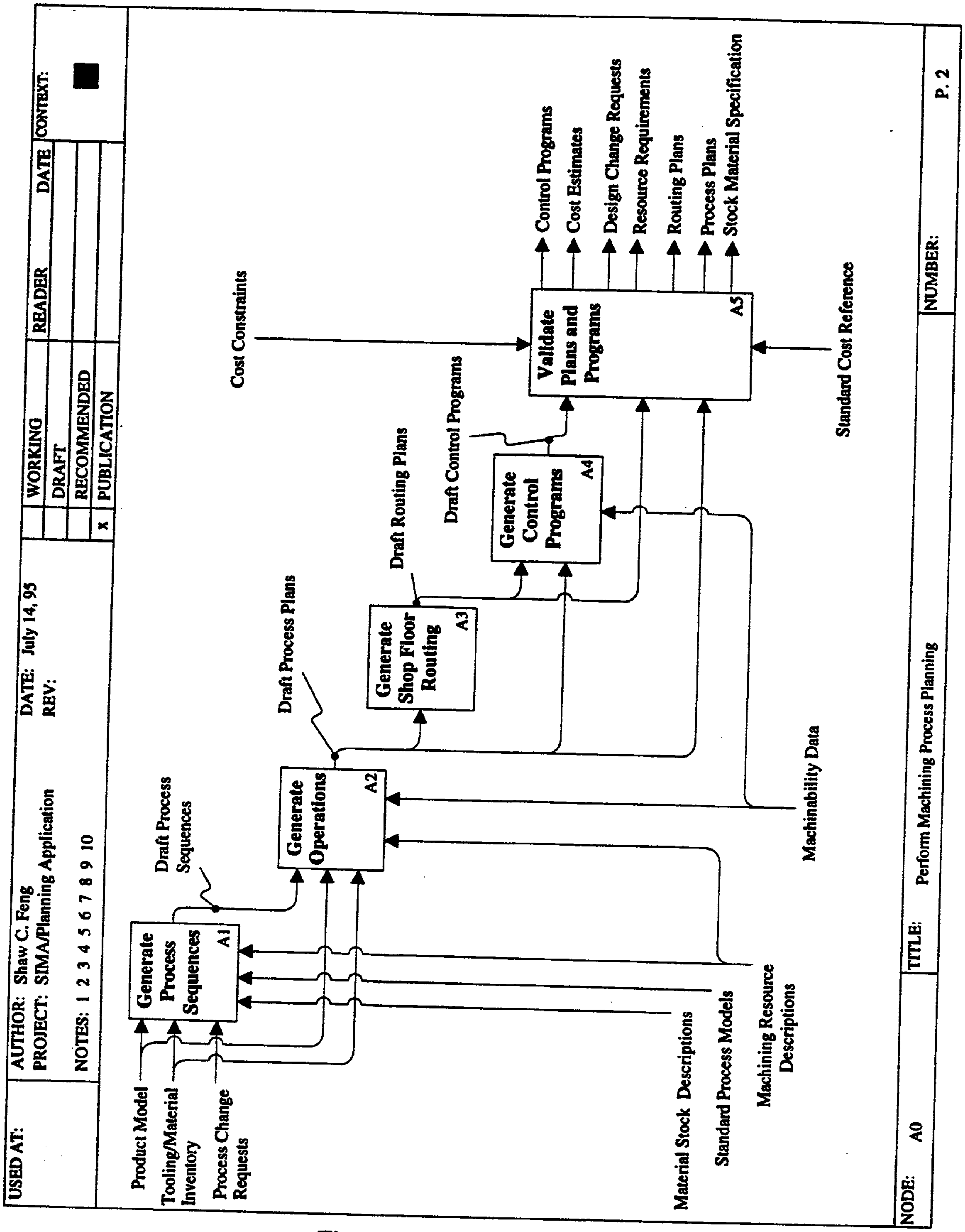

Figure 3 Diagram A0

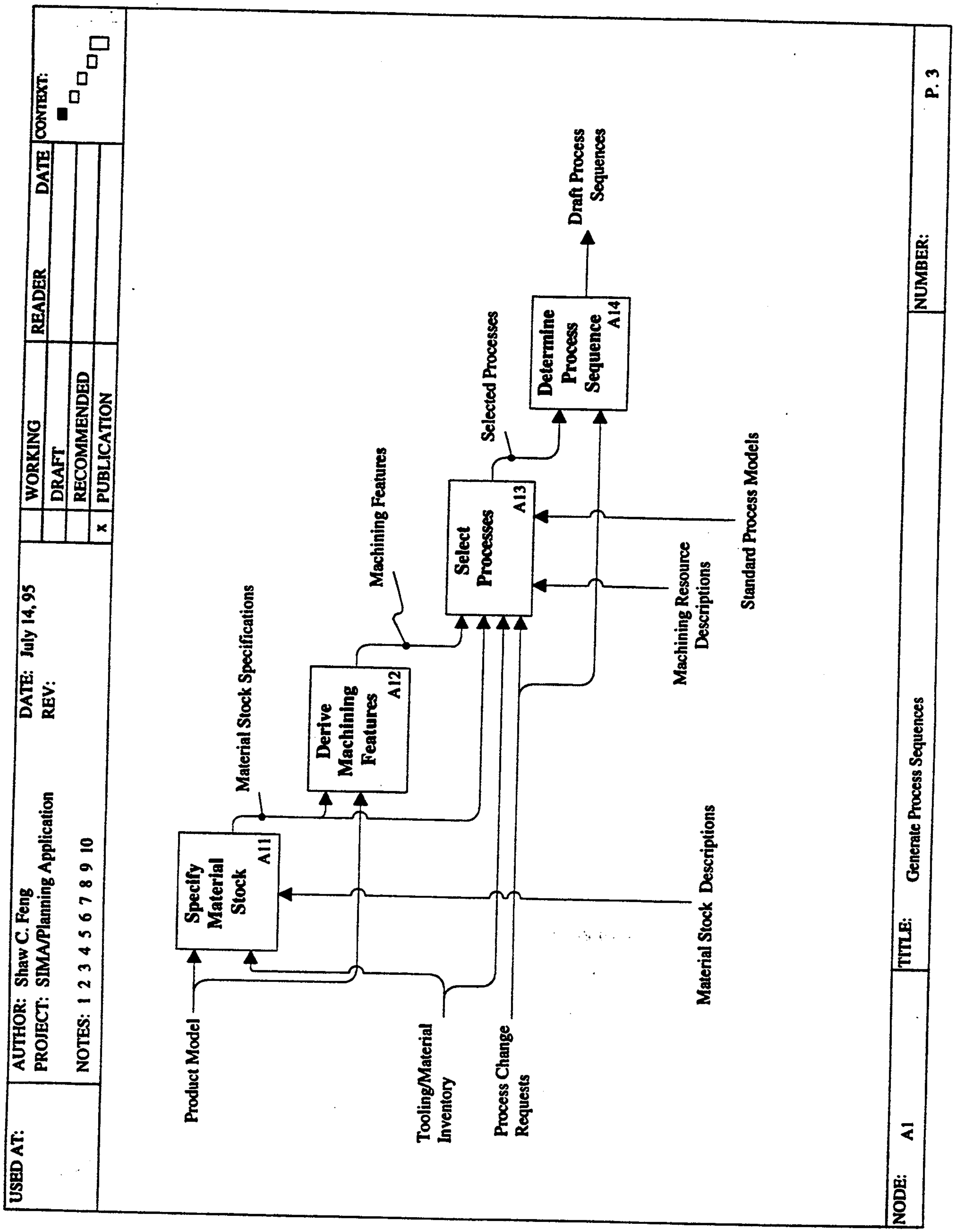

Figure 4 Diagram A1

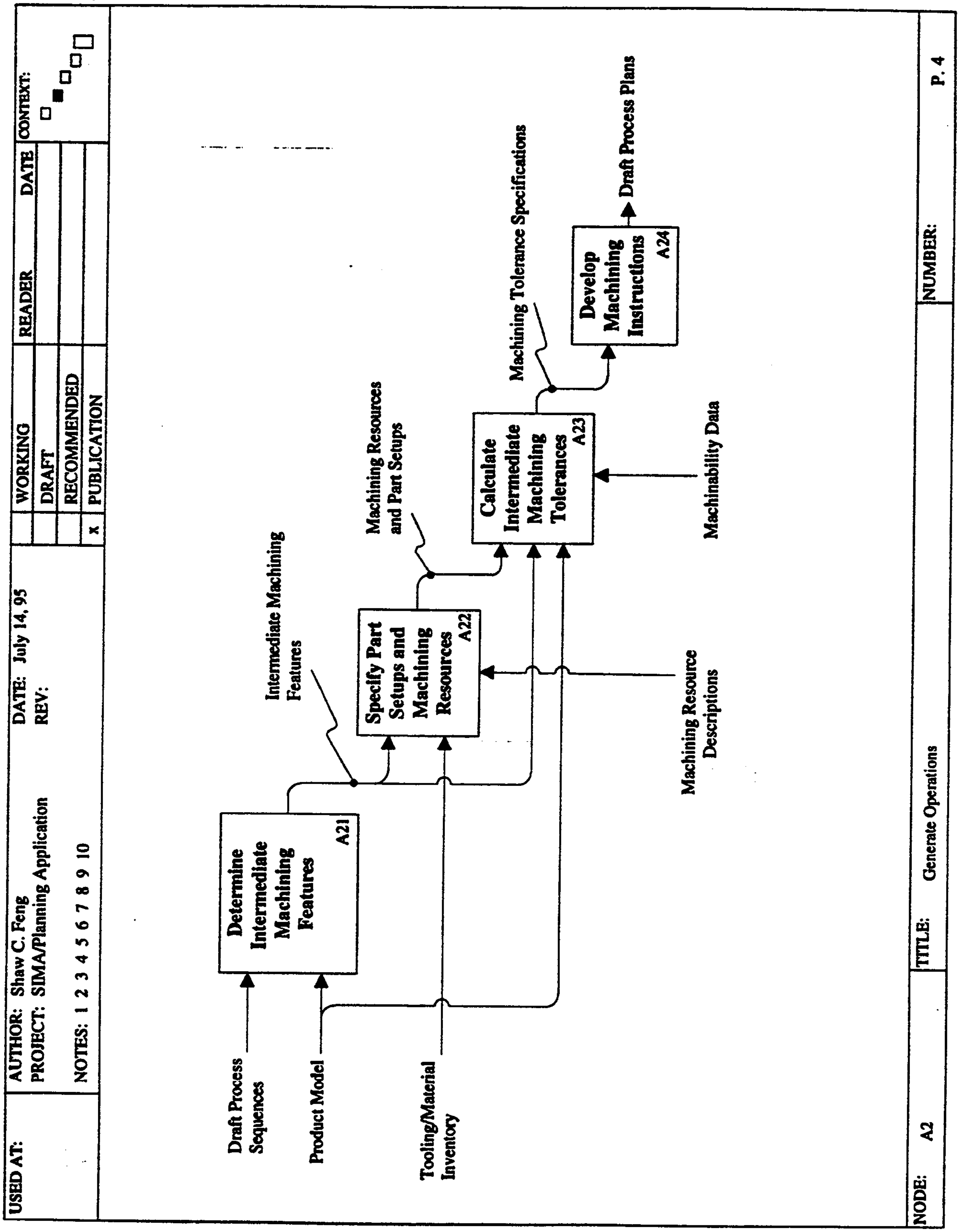

Figure 5 Diagram A2

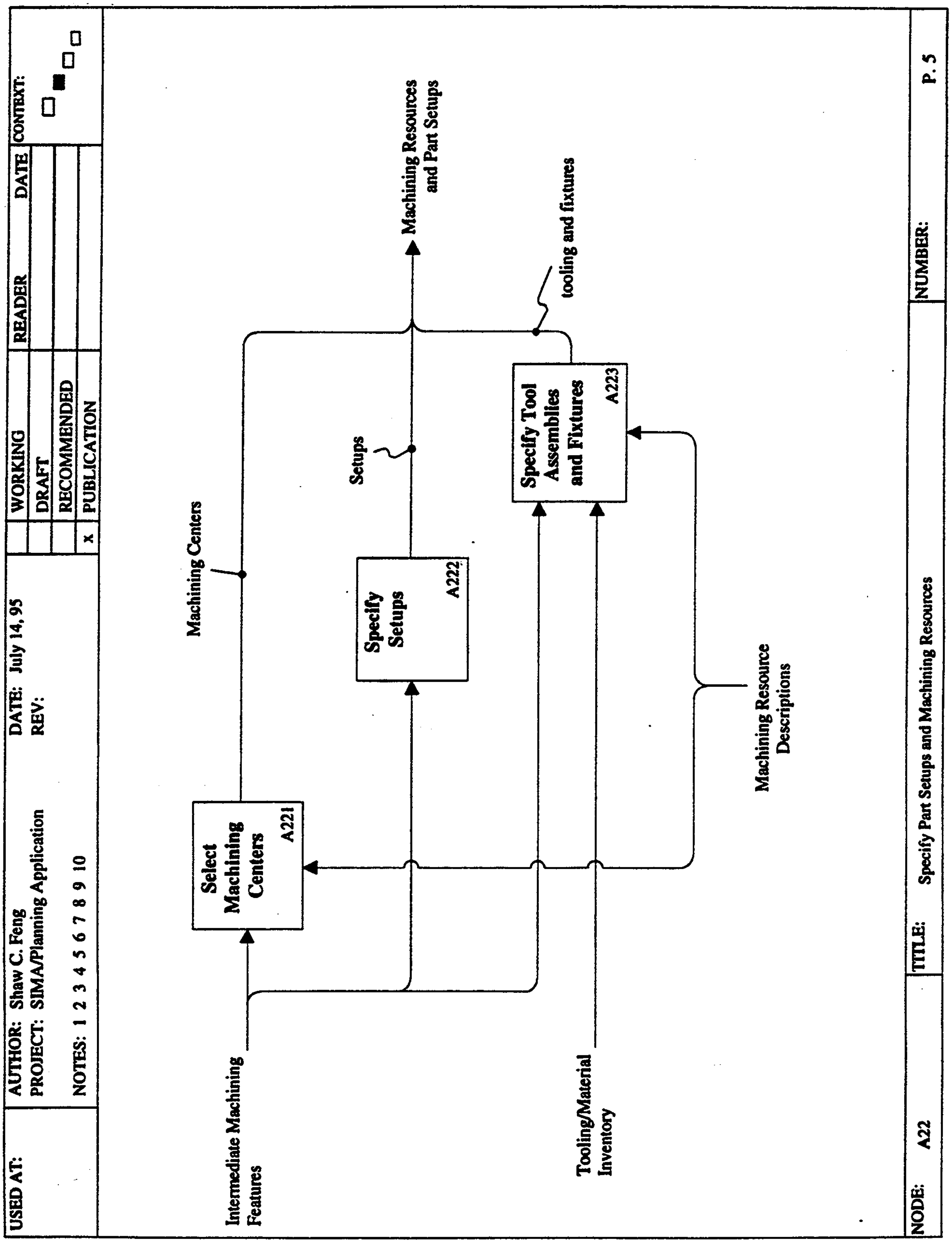

Figure 6 Diagram A22

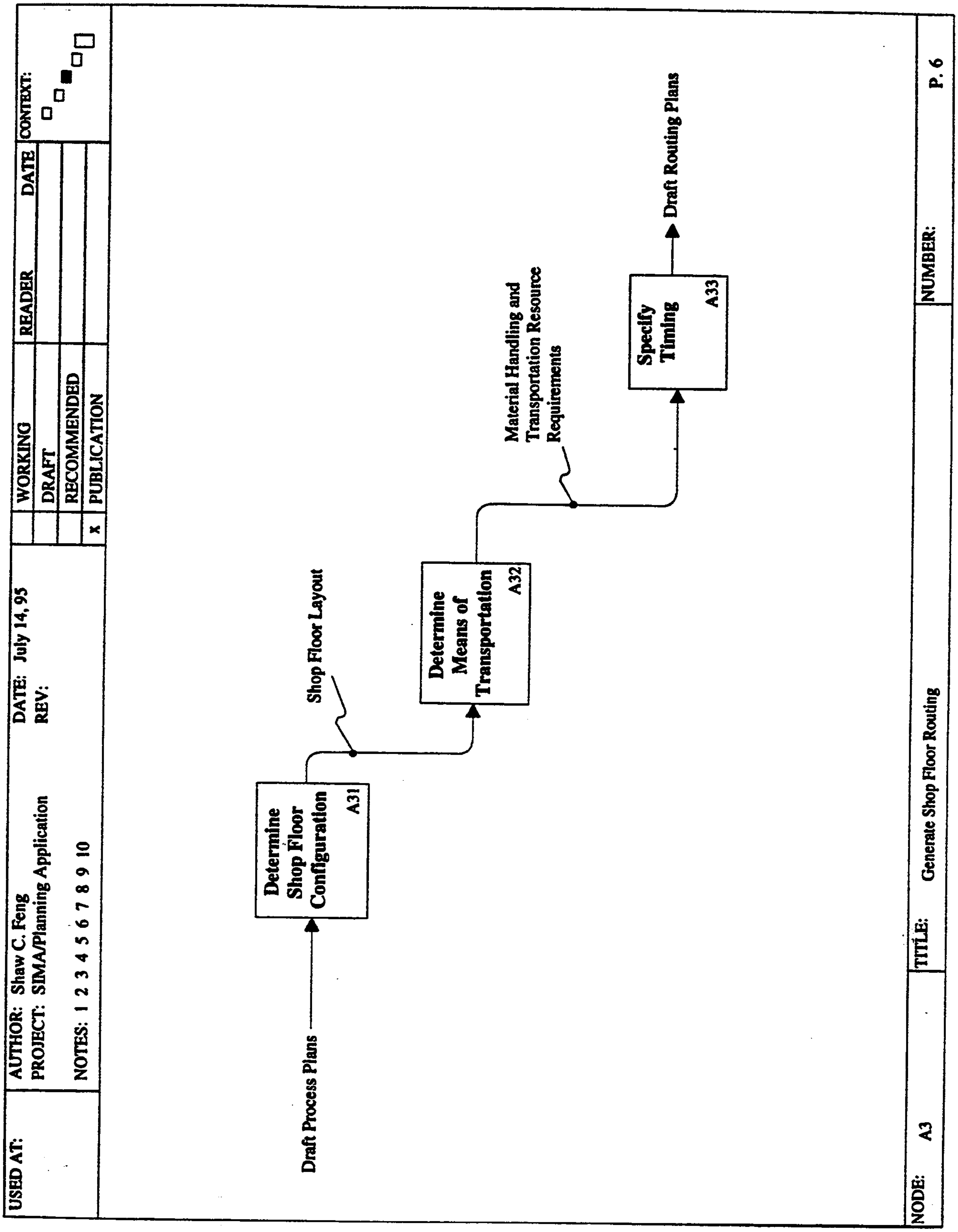

Figure 7 Diagram A3

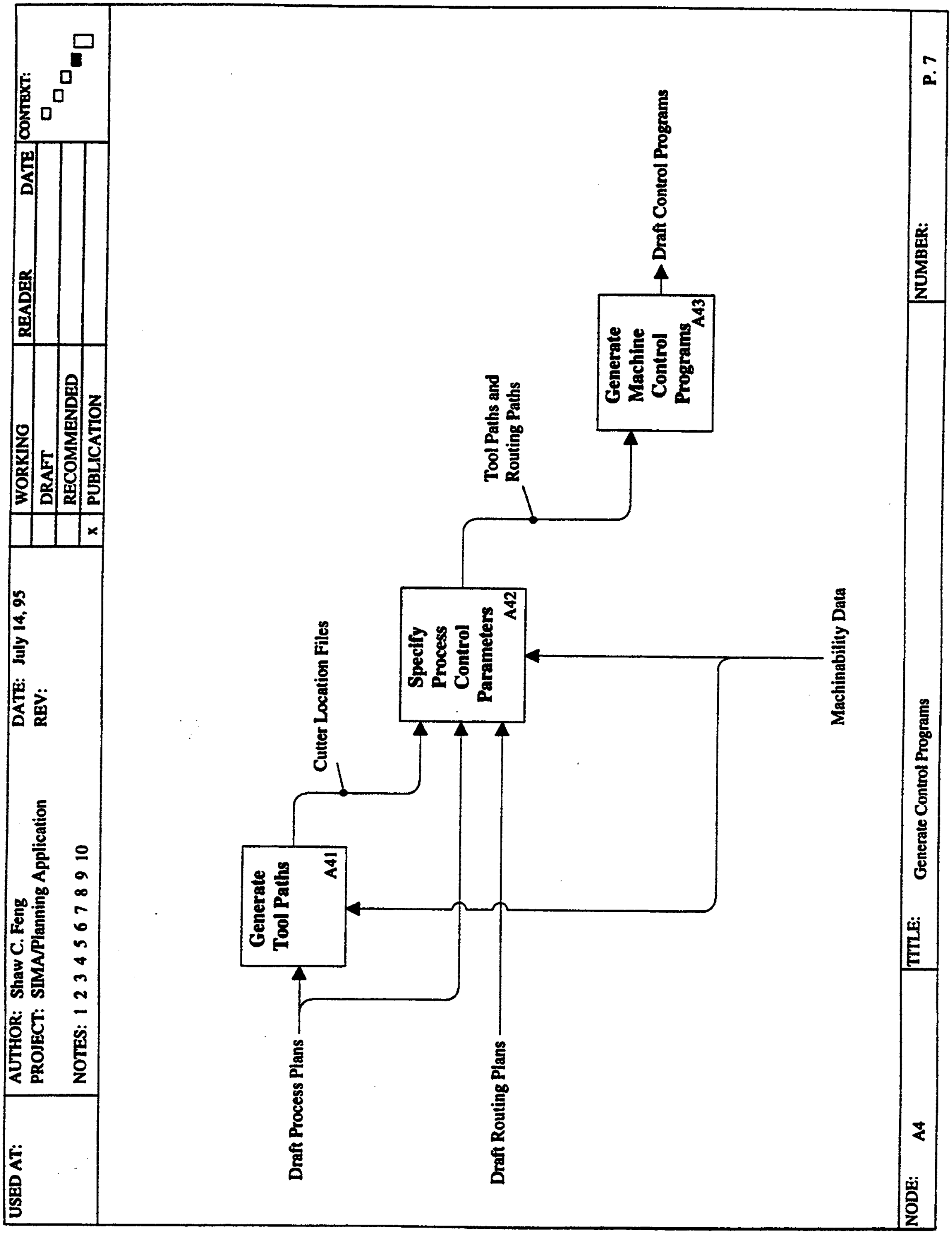

Figure 8 Diagram A4

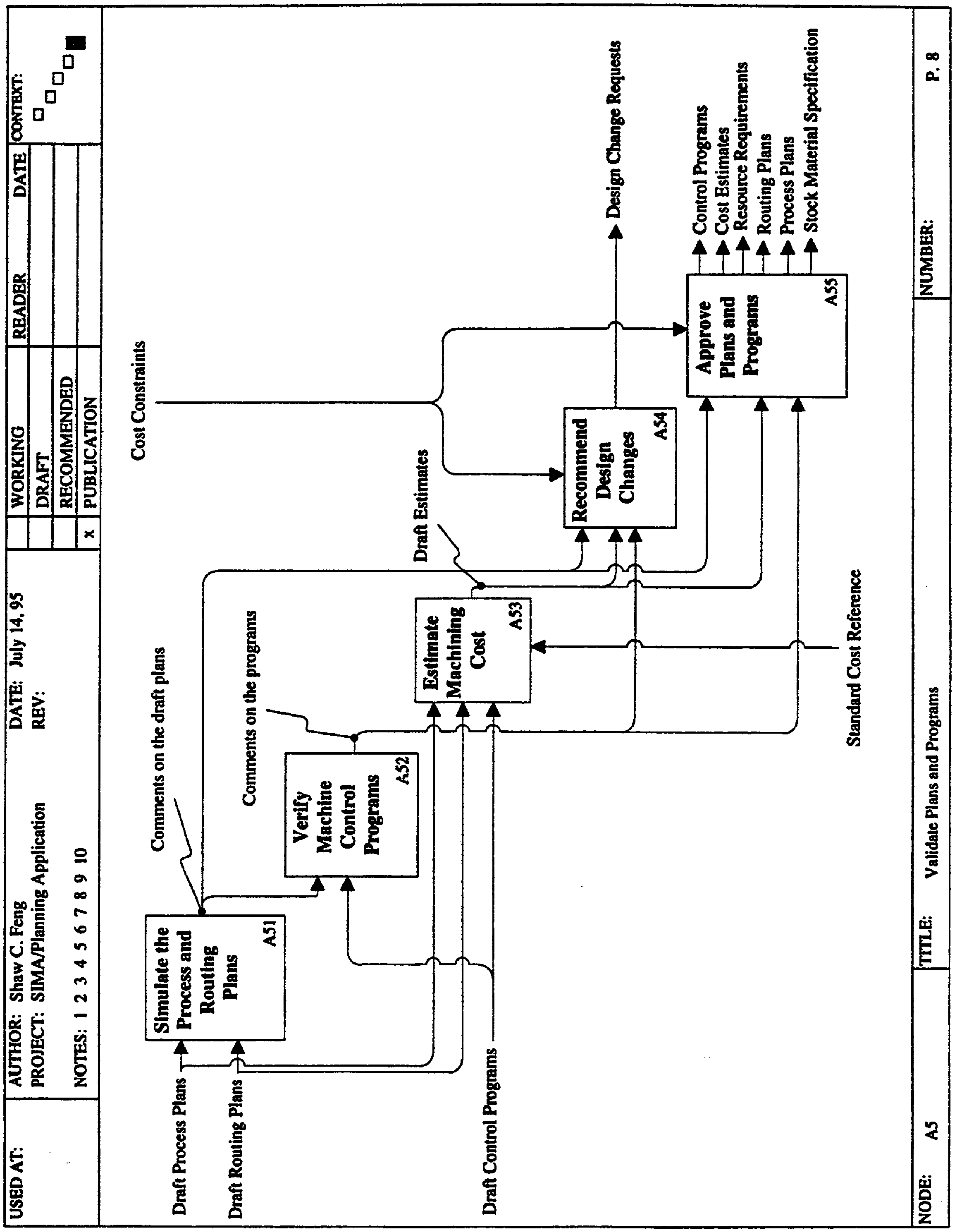

Figure 9 Diagram A5

Activity A12 derives machining features from the selected stock material, based on the design and manufacturing capabilities. The activity is to compare the design with the stock and define zones to be removed from the stock. The zones are machining features, which associate tolerances and datums to the derived features. Also, if necessary, assign GT (Group Technology) codes to the part based on the machining features. The machining features, the output data, are used in the next activity.

Activity A13 selects processes. It is to select appropriate processes to machine the part features to the design specifications, such as cutting, milling, drilling, and turning. A design specification include geometry, tolerances, surface roughness, hardness, and other technological requirements, such as heat treatment and surface treatment.

Activity A14 determines process sequence. The activity sequences the processes to make all the part features.

Activity A2 shows the decomposition of activity A2 into four activities (A21 — A24).

Activity A21 determines intermediate machining features. The activity is to determine intermediate machining surfaces and features in each operation of the generated process sequences.

Activity A22 specifies part setups and machining resources. The activity is to choose the type or a specific machining center, determine the position and orientation of the stock relative to the machine coordinates, and select appropriate cutters, adapters, types of coolant, jigs and fixtures for one or more of the machining processes from the defined process sequence. The part setup determination and machining resources selection are interrelated and are performed in one activity. The machines, tools, and fixtures can be specified by their capabilities or the identifications of specific machines, tools, and fixtures.

Activity A23 calculates intermediate machining tolerances. The activity is to compute tolerance allocations for the machining steps in each operation based on process capabilities. The intermediate tolerances should guarantee the realization of the design requirements of the part.

Activity A24 develops machining instructions. The activity is to specify step-by-step instructions of machining operations. When necessary, special machine, tooling, and setup requirements are specified in the instructions. A machining operation is the material removal work performed by a machine with a tool on a feature.

In Figure 6, Activity A22 is further decomposed into three activities (A221 — A223).

Activity A221 selects machining centers. The activity is to choose the most appropriate machine tools for machining parts based on the design requirements and machining features.

Activity A222 specifies setups. The activity, based on the selected machining centers and the derived machining features, determines the orientations and locations of the workpiece on the machine table relative to the machine coordinates.

Activity A223 specifies tool assemblies and fixtures. The activity is to select appropriate cutters and adapters with respect to machine holders, group tools and adapters into tool assemblies, and identify machine holders in which the individual tools or the tool assemblies fit. Furthermore, specify the fixture and clamping locations for the machining process. For unavailable fixtures, place orders to acquire them.

In Figure 7, Activity A3 is further decomposed into three activities (A31 — A33).

Activity A31 determines shop floor configuration. The activity is to specify the locations of machining centers, workpiece handling machines (e.g., robots), and workpiece transportation machines (e.g., automatically guided vehicles - AGVs) on the shop floor.

Activity A32 determines means of transportation. The activity is to specify types of machines and the operations to handle workpieces into and out of machining centers and transport the workpieces from one machining center to another.

Activity A33 specifies timing. The activity is to specify total time that a workpiece is in a machining center and the time moving from one center to another. Time in a machining center includes loading/unloading time, setup time, and machining time.

In Figure 8, Activity A4 is further decomposed into three activities (A41 — A43) for the generation of machining equipment control programs.

Activity A41 generates tool paths. The activity is to create cutter routes for machining a part based on the derived machining features, product model, setups, the selected machining centers and tools. Linear interpretations, circular interpretations, or spline interpretations along the routes should also be specified. The cutter path is an input to NC program generation.

Activity A42 specifies process control parameters. The activity is to specify parameters that define the machining, routing, and workpiece handling process conditions, such as cutting speeds, feedrates, moving speeds, maximum depths of cut, tool changes, coolant on/off, AGV speed, robot speed, etc.

Activity A43 generates machine control programs. The activity is to develop programs such as NC (numerical control) programs, APT (automated programmed tool) programs, robot programs, and AGV programs for the direct control of machining centers, workpiece handling machines, and workpiece moving machines.

In Figure 9, Activity A5 is further decomposed into five activities (A51 - A55) for detailed specifications.

Activity A51 simulates the process and routing plans. The activity is to use simulation tools to simulate machining operations and workpiece routing to verify the correctness of draft plans.

Activity A52 verifies machine control programs. The activity is to simulate the generated tool paths, machining processes, material handling processes, and material transportations to verify the correctness of the draft control programs.

Activity A53 estimates manufacturing cost. The activity is to assess the machining cost of the parts in terms of labor, time, material, tooling, and machine utilization, etc.

Activity A54 recommends design changes. The activity is to negotiate these changes with design engineers, during the verification process, to enhance the manufacturability of the design and to reduce cost.

Activity A55 approves plans and programs. The activity is to make decisions on whether or not to approve the plans, the programs, and all the data sets that define the required resources and operations based on simulation and verification.

3.2 Glossary for the Data in the Machining Process Planning Activity Model

Input Data:

Part Model:

A computer-interpretable representation of a part. The representation provides the following information about the part: geometry, topology, features, dimensions, tolerances, datum references, material, surface roughness, hardness, coatings, screw threads, and notes on special processing and quality control procedures. The model should provide sufficient data for defining machining processes.

Process Change Requests:

The messages fed back from production planning and scheduling activities requesting changes to current process plans. The requests can be modifications of machine and tooling specifications, procedural changes, tool paths changes, etc. The change requests are usually negotiable between process planners and production planners.

Tooling/Material Inventory:

The data that describe those tools and stock materials that are in the inventory and accessible for parts production. The inventory data include the quantity on-hand and on-order, order status, and types of tools and stock materials. The tools include cutter, adapters, machining center holders, jigs, clamps, fixtures, indexing tables, and types of coolant.

Control and Constraint Data:

Cost Constraints:

The limitation of acceptable machining cost for parts imposed by product planners' and company's decisions.

Mechanism and Resource Data:

Machinability Data:

The reference data that specify machining conditions for using specific cutters and machining centers to machine specific materials. The machinability data are usually found in handbooks or provided by machine tool vendors.

Machining Resource Description:

The form and functional description of available machine and tooling equipment. The form description includes dimensions and the shape of the equipment. The function description includes the capabilities the equipment, such as dimensional variation distributions of machined features, machine speeds versus powers, work volume, fixture rigidity and versatility, machine controller descriptions, cutter descriptions, adapter descriptions, etc.

Material Stock Description:

The form and material properties of the stock material available from the market or specially produced in a factory.

Standard Cost Reference:

Reference data that specify the cost of using a piece of equipment and performing a certain operation. The cost reference data are considered as a standard reference for a company.

Standard Process Models:

A predefined set of operations and related specifications that are used to machine different types of parts.

Output Data:

Control Programs:

Computer-interpretable codes that control machining centers (e.g., NC and APT programs), material handling machines (e.g., robot programs), and material transporting machines (AGV programs). A control program activates the sequence of machine motions and actions.

Cost Estimates:

Assessed costs to machine parts with a specified quantity of production in a specified length of time. The estimated cost includes machine/tooling utilization, labor, materials, scrap rate, estimated lengths of machining processes, and quality control.

Design Change Requests:

Messages fed back to design activities for changes to the product model to improve the part's manufacturability and cost effectiveness.

Process Plans:

Documents that define the sequences of operations for machining the part based on the product model. There is only one primary process plan and can be several alternative process plans.

Resource Requirements:

The specifications of all the machining resources. They include the specifications of all machines, tooling, materials, labor skills, and machining tasks necessary to carry out the plans and execute control programs. Examples are tool lists, machine lists, and labor skill lists.

Routing Plans:

Documents that define the sequences of machines on which workpieces are processed (including machined, handled, and transported). There is only one primary routing plan and can be several alternative routing plans.

Stock Material Specification:

The shape, size, and quantify of the stock material. The specification can include the batch size. The specification is a portion of the final bill of material for a product.

Validation Run Requirements:

The requirements that are needed to specify a production run which validates the developed process plans. The requirements include the specifications of machines, tools, materials, time/cost estimates, labor skills, and the process and routing plans.

Internally Used Data:

Comments on the Draft Plans:

Recommended changes to the draft process and routing plans based on simulation results.

Comments on the Programs:

Recommended changes to the generated machine control programs based on verification results.

Machining Centers:

Identification of the machines, with proper tooling, on which a sequence of machining operations is performed. A machining center provides a tool magazine with a set of tools, drive mechanisms, a motion controller, and a spindle.

Machining Features:

Zones in the material stock to be removed during machining processes. The zones have specified geometries, locations, and orientations relative to the stock.

Setups:

A specification of locations and orientations of the part relative to the machine coordinates and the means of fixing the part on the machine table during the machining process.

Shop Floor Layout:

A specification of locations and orientations of all the machines (including robots) and the areas they cover, tool cribs, AGV routes, material storage places, and other facilities needed in the machining processes.

Material Stock Specifications:

The specifications of materials and the stock geometries. Material stock is a piece of material from which machining processes transform it to a finished part. The piece of material has a fixed form and material properties.

Draft Process Sequences:

The specifications of processes and their sequences for machining parts. The specifications are subject to validation and approval. There is only one primary process sequence and can be several alternative process sequences.

Draft Process Plans:

They are the plans created by process planners based on design specifications and available resources. The plans are subject to validation and approval. See the definition of process plans for detail.

Draft Routing Plans:

The plans created by process planners based on draft process sequences and available resources. The plans are subject to validation and approval. See the definition of routing plans for detail.

Draft Control Programs:

The programs created by process planners based on the draft process and routing plans. The programs are subject to validation and approval. See the definition of control programs for detail.

Intermediate Machining Features:

The features and geometries that define the intermediate shapes at stages of machining processes.

Machining Resources and Part Setups:

See the definitions of machining resources and setups.

Machining Tolerance Specifications:

These are tolerances defined in process planning for the intermediate features. These are derived from target tolerances for the part features by the process planners.

Material Handling and Transportation Resource Requirements:

The specifications of all the needed material handling and transportation machines, fixtures, holders, etc. Material handling machines include, for example, robots and actuators. Transportation machines includes, for example, automatically guided vehicles.

Cutter Location Files:

The files specify cutter paths and machine controls for machining. The files are used to create APT and NC programs.

Tool Paths and Routing Paths:

Tool paths are the route that cutters follow during the machining processes. The routing paths are the route that workpieces follow in moving from one workstation to another.

Draft Estimates:

The cost estimation created by process planners based on draft process and routing plans. The plans are subject to validation and approval. See the definition of cost estimates for detail.

4 Conclusion

The machining process planning activity model described in this paper has been developed as part of an effort to integrate manufacturing software systems. Specifically, the effort is on integrating computer aided process planning systems with design, production simulation, and scheduling systems. The purpose of this activity model is to capture information required in the machining planning process based on transforming material stocks to finished parts according to product models and NC machining process capability limitations. The activity model was specifically developed for the automated machining process using numerical controllers, which are commonly used in industry. The IDEF0 diagrams capture the activity model that specifies functional components of process planning and data requirements for the functional components to process. The planning activities produce process plans, routing plans, cost estimation, machine and tooling requirements, machine control programs, and comments on the design. The input, control, resource, and output data identified in the activity model are shared by and exchanged among different computer aided process planning systems, computer aided design systems, production simulation systems, and production scheduling systems.

The next phase in the development of an integrated environment is to generate data models to characterize the structure of the information identified in this activity model. Work such as developing a process plan data model, a manufacturing resource data model, and a machined part design data model are necessary and some of this work is underway.

5 References

1. Background Study: Requisite Elements, Rationale and Technology Overview for the 'Systems Integration for Manufacturing Applications' (SIMA) Project, edited by E.J. Barkmeyer, T.H. Hopp, M.J. Pratt, and R. Rinaudot, NISTIR 5662, the National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, September 1995.

2. SIMA Reference Architecture Part I: Activity Models, ed. E.J. Barkmeyer, in publication.

3. Integrated Computer-Aided Manufacturing (ICAM) Architecture Part II, Volume IV - Functional Modeling Manual (IDEF0), Material Laboratory, U.S. Air Force Wright Aeronautical Laboratories, June 1981.

4. Ferreira, P.M., Lu, S.C.-Y., and Zhu, X., "Conceptual Model for Process Planning," Consortium for Advanced Manufacturing International (CAM-I), Arlington, Texas, 1990.

5. Bjorke, O. And Myklebust, O. (eds.), "IMPPACT - Integrated Modelling of Products and Processes using Advanced Computer Technologies," Tapir Publishing, Trondheim, Norway, 1992.

6. Lindsay, K., "Automated Airframe Assembly Program," Vol. 1, Wright Laboratory, Wright-Patterson Air Force Base, Ohio, May 1992.

7. Fulford, D., Santos, H., and Tu, M., "Automated Airframe Assembly Program," Vol. 2, Wright Laboratory, Wright-Patterson Air Force Base, Ohio, May 1992.

8. ISO/CD 10303-213, "Product Data Representation and Exchange - Part 213: Application Protocol: Numerical Control Process Plans for Machined Parts," TC184/SC4/WG3 document 357, April 1995.

9. ISO/WD 10303-224, "Product Data Representation and Exchange - Part 224: Application Protocol: Mechanical Product Definition for Process Planning Using Form Features," TC184/SC4/WG3 Document 405, June 1995.

10. Feng, S. "Dimensional Inspection Planning Based on Product Data Standards," NISTIR 5183, the National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, May 1993.